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A LITHIUM BROMIDE ABSORPTION CHILLER WITH COLD STORAGE

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ABSTRACT

A LiBr-based absorption chiller can use waste heat or solar energy to produce useful space cooling for small buildings. However, operating this absorption chiller at high ambient temperatures may result in performance degradation, crystallization in the absorber, and high water consumption for heat rejection to the ambient. To alleviate these issues, a novel LiBr-based absorption chiller with cold storage is proposed in this study. The cold storage includes tanks for storing liquid water and LiBr solution, associated piping, and control devices. The cold storage allows shifting heat rejection to the periods with lower ambient temperatures such as nighttime. The difference between the ambient temperatures at nighttime and daytime could be significant in many areas of the world. An ambient temperature reduction of 10°C could increase the single-effect absorption cycle COP (Coefficient Of Performance) from 0.71 to 0.75. Alternately, if the COP is kept the same, this ambient temperature reduction can lead to a larger difference between the ambient and condenser or absorber temperature, resulting in lower water consumption for a hybrid-cooling tower or a smaller air-cooled heat exchanger for absorber or condenser. Unlike a conventional absorption chiller, the proposed system is designed to allow the LiBr solution to crystallize in the absorber.

The proposed system is evaluated at a representative climate condition and cooling load profile for small buildings with in-house thermodynamic models and consistent fluid properties and assumptions. The performance, size of the storage tank, and the water consumption of the proposed system is compared to those of a conventional LiBr-based absorption chiller. A parametric study is performed to investigate the impacts of the ambient wet bulb temperature and solution flow rate on chiller performance.

1. INTRODUCTION

A LiBr absorption chiller (Herold et al., 1996) can use low-grade waste heat to produce useful cooling for residential and commercial buildings. In this absorption chiller, water is the refrigerant and LiBr-H_2O solution the absorbent. This refrigerant pair is non-flammable and non-toxic and has no associated environmental hazard, ODP (Ozone Depletion Potential), or GWP (Global Warming Potential). However, the performance of the absorption chiller drops quickly as the ambient temperature increases. In addition, the LiBr-H_2O solution tends to crystallize at high ambient temperatures.

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In most conventional cooling systems, there are mainly two types of cold storage. These two types store energy via sensible and latent heat (Saito, 2002, Dinçer and Rosen, 2002). The sensible cold storage releases energy stored when a substance changes from one temperature to another. The latent cold storage makes use of energy stored when a substance changes from one phase to another, for instance by melting. The cold storage tanks for these two cold storage types mentioned above have lower than the environment temperature. Accordingly, the cold energy losses must be considered during the storing period, especially when energy is stored over a long time period.

The working principle of absorption cold storage (Kazuhiko, 2002, Bolin and Olsson, 2009, Bolin et al., 2010) uses LiBr or other desiccant solution and water to store thermal energy via desorption/absorption. Using this method, the cooling capacity can be preserved for a long term with no pollution and no cooling energy losses, and it is readily released when needed by connecting the absorber to the evaporator. The energy density of the storage system could be very high, compared to conventional thermal energy storage systems. Several researchers (Kessling et al., 1998, Liu et al., 2005) uses concentrated aqueous desiccant solution to store energy for dehumidification applications. This energy storage works only if the concentration difference between the solution at the inlet and at the outlet of the regenerator is considerable. This study proposes a new method to integrate a LiBr absorption chiller with the absorption cold storage to increase energy savings.

2. SYSTEM CONCEPT

Figure 1 shows schematics of a conventional single-effect LiBr absorption chiller and the proposed chiller using LiBr and water to store energy. Each schematic is superimposed on a Dühring plot of the working fluid. To clarify the fundamental difference between the two systems, the schematics include only the major components. The conventional absorption chiller consists of a desorber, condenser, evaporator, absorber, heat exchanger, pump, and two valves. The LiBr solution at state point 3 is pumped into the desorber where external heat is added to the solution to boil off the refrigerant. As a result, the LiBr solution becomes concentrated and leaves the desorber at state point 4. The concentration at state point 4 must be kept on the left side of the crystallization line as shown in Figure 1. The typical concentrated LiBr solution contains around 63% LiBr by weight. The concentrated solution passes through the solution heat exchanger and exchanges heat with the solution leaving the absorber. After leaving the solution heat exchanger at state point 5, the concentrated solution is throttled through the valve. The resulting low-pressure concentrated solution at state point 6 enters the absorber where the concentrated solution absorbs vapour supplied by the evaporator to become diluted and where the heat of this absorption process is rejected to the ambient. The resulting diluted solution at state point 1 is pumped to a higher pressure at state point 2. The solution at state point 2 is passed through the solution heat exchanger and is heated up by the concentrated solution. After leaving the heat exchanger at state point 3, the diluted solution returns back to the desorber. After leaving the desorber at state point 7, the refrigerant enters the condenser where refrigerant vapour is condensed into liquid and where the heat of condensation is rejected to the ambient. The resulting liquid refrigerant at state point 8 is throttled through the valve to a lower pressure. In the throttling process, some of the liquid is flashed into vapour and the temperature of the refrigerant is significantly reduced. The resulting two-phase refrigerant at state point 9 enters the evaporator where the refrigerant evaporates and absorbs heat from the surroundings. The resulting vapour at state point 10 flows into the absorber to contact with the LiBr solution.

As shown in Figure 1, the proposed system is similar to a conventional LiBr absorption chiller, including all the same major components. However, several differences exist between these two systems. First, the LiBr solution is designed to crystallize in the absorber for the proposed system. A heat pump allowing the solution to crystallize in the absorber had been successfully designed before (Bolin and Olsson, 2009). In contrast, a conventional absorption chiller does not allow the LiBr solution to crystallize in any part of the system. As a result, the concentration of the LiBr solution leaving the desorber can be much higher for the proposed system than that for a conventional system. In Figure 1, this LiBr solution for the proposed system has 66.5% LiBr by weight while it has 63% for a conventional system. The working fluid crosses the crystallization line for the proposed system but not for a conventional system. The COP of an absorption chiller increases with an increase in LiBr mass fraction at state point 4 (X_4), which is discussed in the Results section. Second, the absorber and evaporator in the proposed system are divided into several sub-absorbers and -evaporators such that the absorption refrigeration for these pairs of absorbers/ evaporators can take place in various sequences. Therefore, while some sub-absorbers are in the process of crystallization, the other sub-absorbers can absorb the vapour from their corresponding evaporators. The combined volume of these sub-absorbers is sized for a desired amount of stored energy. The design also allows all the sub-absorbers to absorb the vapour at the same time. Third, a water storage tank is placed between the valve and condenser. The water stored in this tank will be used in the evaporator and the volume of the storage tank is sized such that the heat of evaporation for the stored water is equal to the desired amount of stored energy.

The chiller for the proposed system operates at relatively low ambient temperatures and shut down at relatively temperatures. At relatively high temperatures, the stored energy is used according to cooling demand. At the end of the high-temperature period, the stored energy is completely exhausted and the chiller starts to generate additional cooling for later use. At the end of the low-temperature period, the maximum amount of energy is stored in the proposed storage device.

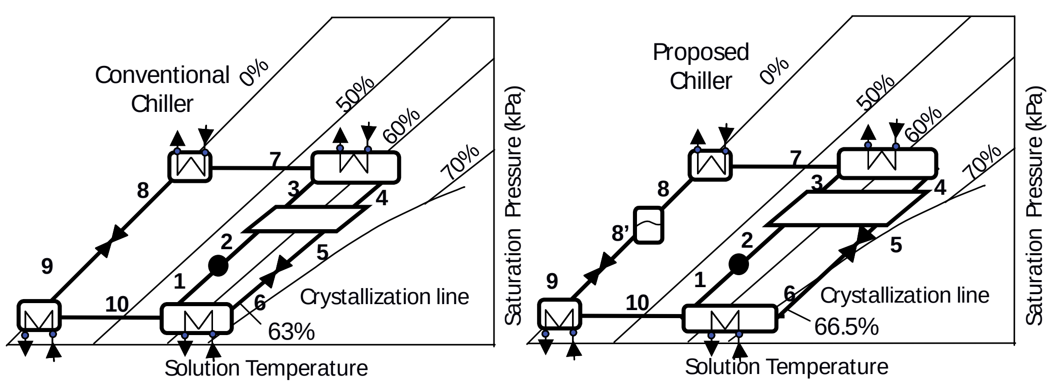

Figure 1. Schematics of conventional and proposed single-effect absorption chiller

3. MODELING

Three thermodynamic models were developed using Engineering Equation Solver (EES) (Klein, 2010). They include the proposed system and a conventional single-effect LiBr chiller with and without water storage. EES integrally provides the thermodynamic properties of steam (Harr et al., 1984), humid air (Lemmon et al., 2000), and LiBr solution (Patek and Klomfar, 2006) used for this modelling work. All the three refrigeration systems reject heat through wet cooling towers. The major assumptions for the thermodynamic models can be found in Table 1. The heating source for the desorber can be the heat from engine exhaust gas, natural gas, hot water, or steam. To make a fair comparison, the maximum cooling capacities for three different options are assumed to be the same. T_{10}, the temperature of state point 10, is assumed to be 5°C for all the three cooling systems. The temperature approaches for the condenser and absorber heat exchangers are 5 and 3.9°C, respectively. X_4 is 0.665 and 0.624 for the proposed system and a conventional absorption chiller, respectively. X_4 for the proposed system is significantly higher than that for a conventional system because the proposed system allows LiBr solution to crystallize in the absorber. The LiBr solution for a conventional absorption chiller is always kept away from the solubility limit with a safety margin to avoid crystallization; thus, X_4 is kept around 0.63. The temperature approach is 10°C between the cold water leaving the cooling tower and the wet bulb temperature of the ambient air and 4°C between the warm water entering the cooling tower and the wet bulb temperature of the air leaving the cooling tower.

To evaluate the impacts of cold storage systems on energy and water consumption, it is assumed that the three cooling systems are used to cool a commercial building in Fort Worth, TX in a typical summer day (DOE/NREL/ASE, 2010). The cooling demands and ambient conditions for this commercial building can be found in Figure 2. The highest dry-bulb temperature is 36.1°C at 4 pm while the lowest temperature is 22.8°C at 5 am. The wet-bulb temperature varies very little during the day and ranges from 20.2 to 24.5°C. The cooling load is around 30 kW during the day and reduced to 5 kW at night.

Table 1. Major assumptions for the thermodynamic models for the cooling system discussed here.

	Proposed System	**Conventional Chiller**	**Conventional Chiller with Water Storage**
Absorption Chiller			
Maximum Cooling Capacity, kW	30	30	30
T_{10}, °C	5	5	5
Temperature Approach for HX_C, °C	5	5	5
Temperature Approach for HX_a, °C	3.9	3.9	3.9
X_4	0.665	0.624	0.624
Heat Loss of Desorber to Ambient, kW	0.2	0.2	0.2
Pump Efficiency	0.7	0.7	0.7
Pressure Drop for each side of HX_s , kPa	25	25	25
Effectiveness of HX_s	0.64	0.64	0.64
Cold Storage Capacity, kW-hr	262.5	0	262.5
Wet Cooling Tower			
Air Relative Humidity Leaving Tower	95%	95%	95%
Air Draft Loss, kPa	0.75	0.75	0.75
Fan Efficiency	0.7	0.7	0.7
Cold Water Temperature Approach to Ambient Wet Bulb Temperature, °C	10	10	10
Warm Water Temperature Approach to Air Wet Bulb Temperature, °C	4	4	4

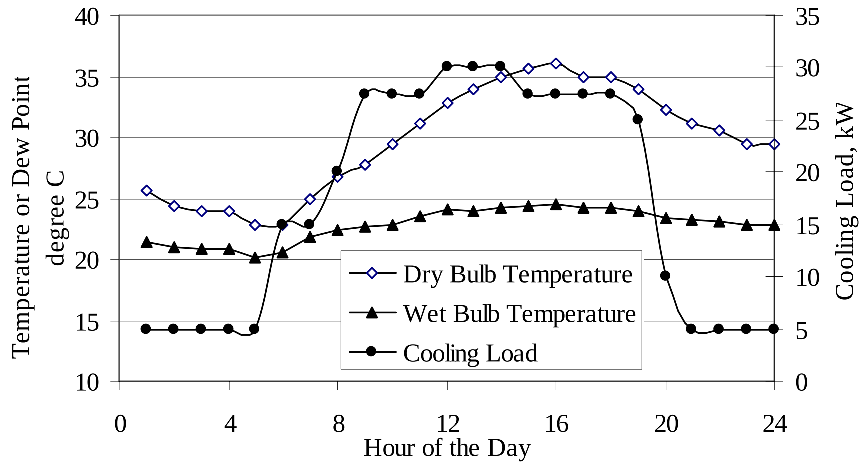

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Figure 2. Ambient dry and wet bulb temperatures and cooling load during a summer day

4. RESULTS

Thermal energy is conventional stored in the form of sensible heat change by changing the temperature of a substance such as water, brick, and salt and in the form of latent heat change by changing the phase of a substance such as ice. Unlike conventional thermal storage systems, the proposed energy storage is charged by separating water from LiBr aqueous solution to create a chemical potential and discharged by absorption refrigeration. Table 2 shows the energy densities of conventional sensible and latent energy storages and the proposed absorption refrigeration system. The energy density is defined as (energy stored)/(volume of working fluid). The temperature difference for the sensible cold storage is assumed to be 7°C to calculate the energy density of the sensible heat storage. The calculated energy density for the absorption refrigeration storage is ~2 times that for the latent heat of ice and ~20 times that for the sensible heat of water. This energy density is directly related to the size of the storage system, one of the critical parameters for selecting a storage system.

Table 2. Energy densities of three different cold storages

	Cold Water, Sensible Heat	Ice, Latent Heat	Water/LiBr, Chemical Potential
Energy Densities, kJ/Liter	29	334	592

In addition to high energy density, the absorption refrigeration storage system is not subjected to the heat loss to the ambient. In contrast, the conventional sensible and latent heat storage systems will lose energy to the ambient. Therefore, the sensible and latent heat storage systems require insulation to minimize such a heat loss. Insulation could be one of major cost items for an energy storage system.

Figure 3 shows the wet bulb temperature vs. thermal COP (cooling output divided by heat input to desorber) at various cooling loads for a LiBr absorption chiller with a wet cooling tower. The thermal COP increases with an increase in cooling load and with a decrease in the wet bulb temperature. Since the wet bulb temperature represents the heat sink temperature for a wet cooling tower, the thermal COP is strongly correlated the wet bulb temperature instead of the dry bulb temperature. At night, an absorption chiller is more efficient due to lower ambient temperatures and electricity is likely cheaper. Therefore, it may be advantageous to operate a chiller at full capacity at low ambient temperatures such as nighttime and to store additional cooling for the use during the day.

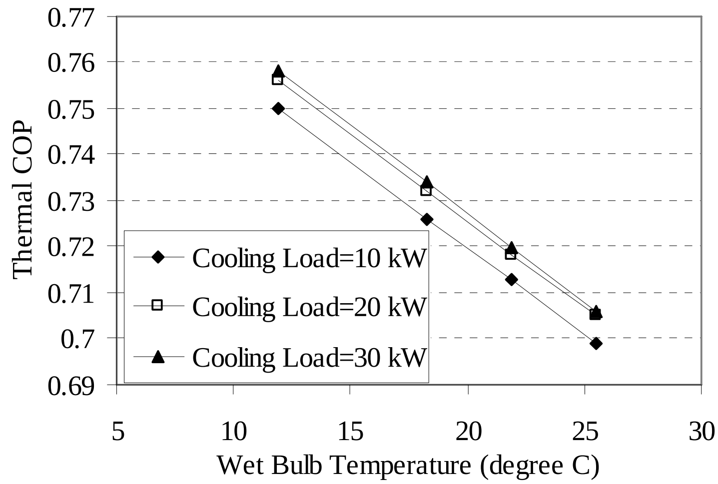

Figure 3. Thermal COP as a function of wet bulb temperature and cooling load

A cold storage would enable an absorption chiller to operate at full power at low wet-bulb temperatures. Figure 4 shows the cooling loads and COP's of the cooling systems with and without cold storage in a sample day in July in Fort Worth, TX. These cooling systems reject the heat to the ambient via wet cooling towers. Without cold storage, the chiller must exactly follow the cooling demand for 24 hours as shown in Figure 4. The total accumulated cooling for 24 hour is 412.5 kW-hr. The thermal COP of the chiller ranges from 0.697 to 0.716.

Figure 4 also includes the performance of the cooling system with a chilled water storage. The storage is sized such that the chiller can always output a cooling rate of 30 kW at relatively low wet-bulb temperatures. The storage can store cooling water with cooling capacity of 262.5 kW-hr. The chiller operates only 13.75 hrs in a day and provides required cooling: a total accumulated cooling of 412.5 kW-hr. The thermal COP for the chiller with a chilled water storage varies from 0.715 to 0.726, higher than that for the chiller without cold storage.

Figure 4 also shows the performance of the proposed system using LiBr/ water to store energy up to 262.5 kW-hr. The energy storage allows the chiller to operate only 13.75 hrs in a day and to provide required cooling. The thermal COP for the proposed system is ~0.03 higher than that for a conventional absorption chiller with a chilled water storage mainly because X_4 for the proposed system is much higher than that for a conventional absorption chiller. Figure 5 shows the thermal COP and solution flow rate as a function of X_4. In this calculation, it is assumed that the chiller can operate even with the solid salts in the absorber. Due to the limited space, the design of the absorber allowing the desiccant solution to crystallize is not discussed in this paper. As X_4 increases from 0.6 to 0.68, the thermal COP increases from 0.69 to 0.75 and the solution flow rate decreases from 0.23 to 0.07. The decrease in the solution flow rate means carrying the same amount of refrigerant with reduced solution flow rate. The decrease in the carrier solution flow rate results in the decrease in the required heat for the desorber; thus, the thermal COP increases with a decrease in solution flow rate and with an increase in X_4.

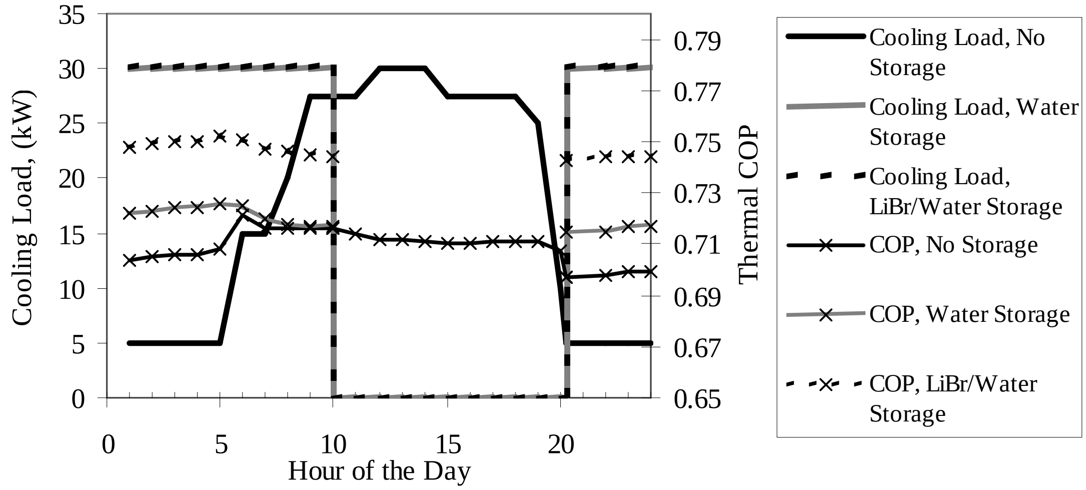

Figure 4. Cooling loads and thermal COP's of three cooling systems for 24 hrs.

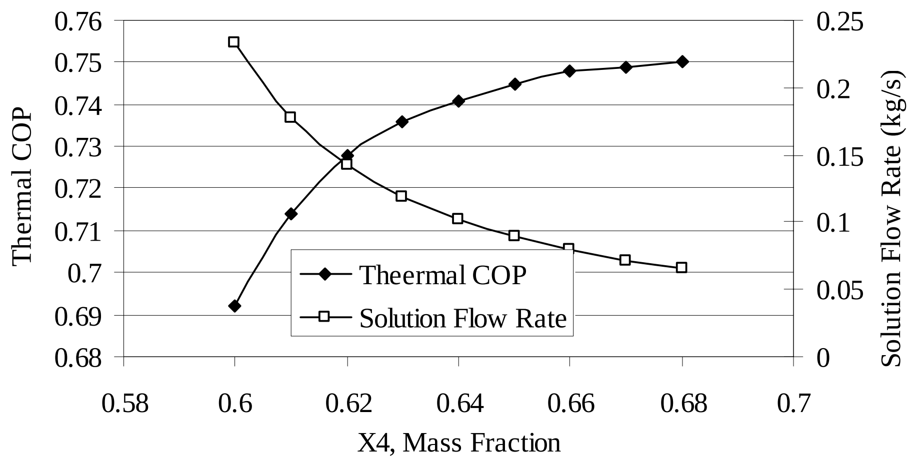

Figure 5. Effect of X_4 on solution flow rate and thermal COP

Table 3 shows the energy and water consumptions for operating a single-effect LiBr chiller with and without cold storage. The ambient conditions for chiller operation are described in Figure 2. Table 3 shows that a cold storage reduces required heat, electricity, and water for chiller operation. Of these three cooling systems, the system with the LiBr/water storage consumes the least amount of energy and water. Additionally, the volume of the LiBr/water storage is ~1/20 that of the water storage.

Table 3 – Energy and water consumptions for operating a single-effect LiBr chiller during a hot day

	Required Heat, kW-hr	Consumed Electricity, kW-hr	Consumed Water, kg	Minimum Storage Volume,

				m^3
Chiller without Storage	580	19.7	1266	0
Chiller with Water Storage	573	16.3	1168	32.3
Chiller with LiBr Storage	556	16.3	1148	1.7

5. CONCLUSION

A cold storage enables a chiller to operate at relatively low ambient temperatures and to store additional cooling for the use during the day, leading to energy savings. The proposed cooling system using LiBr/Water to store energy has the highest COP, consumes the least energy, and occupies the least space. The volume for the proposed energy storage system is ~1/20 that for a conventional cooling water storage system. The proposed energy storage system is not sensitive to the heat loss to the ambient. Since the proposed system allows solution to crystallize in the absorber, the damage associated with crystallization can be minimized.

The economics of the proposed cooling system should be evaluated to understand the commercialization viability of the proposed system in the future. LiBr is much more expensive than LiCl or $CaCl_2$. To reduce the cost of the proposed system, it may be possible to use LiCl, $CaCl_2$, or desiccant mixtures to replace LiBr.

NOMENCLATURE

COP Coefficient Of Performance
HX Heat Exchanger
T Temperature, ºC
X Mass fraction of LiBr solution

Other subscripts:
a absorber
c condenser
4 state point 4

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